Equilibration in Orbiting Reactions

B. Shivakumar
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511, and Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

D. Shapira and P. H. Stelson
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

M. Beckerman
Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37831

B. A. Harmon
University of Virginia, Charlottesville, Virginia 22901, and Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

K. Teh
Physics Department, Vanderbilt University, Nashville, Tennessee 37235, and Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

and

D. A. Bromley
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511
(Received 14 April 1986)

Forward-angle yields of targetlike products in reactions between a ^{28}Si beam and a ^{14}N target have been measured at laboratory energies between 100 and 170 MeV. The ^{12}C and ^{16}O yields are found to be higher than those of ^{14}N over the measured range of energies. This is interpreted as evidence for the equilibration of charge and mass in orbiting reactions.

PACS numbers: 25.70.Jj, 25.70.Lm

The intimate interaction between light heavy ions often results in the formation of an orbiting dinuclear complex (DNC). Such a composite is characterized by a dinuclear shape, which distinguishes it from a compound nucleus. The direct fragmentation of such a DNC we therefore expect to be dominated by yields of complex fragments, as has been documented in the literature.[1-6] This is to be contrasted to the process of light-particle evaporation which dominates compound-nucleus decay. Other distinguishing features of the orbiting process are the strong memory of the entrance channel,[4] and lifetimes[6] intermediate between those expected for direct and compound-nucleus processes. Studies of the alignment[5,7,8] of orbiting yields and the energy division[7,8] between orbiting products have shed additional light on the dynamics of the process. Information on the nature and extent of particle exchange in such interactions has, however, been lacking and is essential in establishing the sequence of events which lead from dissipative collisions through the intermediate orbiting process to compound-nucleus formation. We therefore investigate, herein, whether the DNC's formed in orbiting interactions live sufficiently long to permit extensive particle exchange. This would establish whether or not such exchange occurs within a dinuclear configuration and prior to the formation of a compound nucleus. The results of our experiments demonstrate, for the first time, that such orbiting complexes indeed live sufficiently long for the exit-channel yields to be determined by phase-space considerations (we refer to the resulting distribution as reflecting charge and mass equilibration).

Existing orbiting measurements[1-6] do not provide compelling evidence for a phase-space determination of exit-channel yields. To obtain more definitive data requires the formation of a DNC via an entrance channel which is not the one most favored on energetic grounds for breakup, and at energies where there are a number of accessible exit channels (both inelastic and transfer). It is for this reason that we have selected the $^{28}Si+^{14}N$ system for study. Figure 1 shows a schematic plot of the potential energies in the ground state of dinuclear particle-transfer channels open to the $^{28}Si+^{12}C$ and $^{28}Si+^{14}N$ interactions. The mass different (Q value) between the entrance channel and each of the other channels has been adjusted by the appropriate differences in the Coulomb, nuclear, and centrifugal energies. A value $l=23$ for the orbital angular momentum has been chosen for this plot. Within each particle channel are channels for inelastic excitation and these determine the corresponding

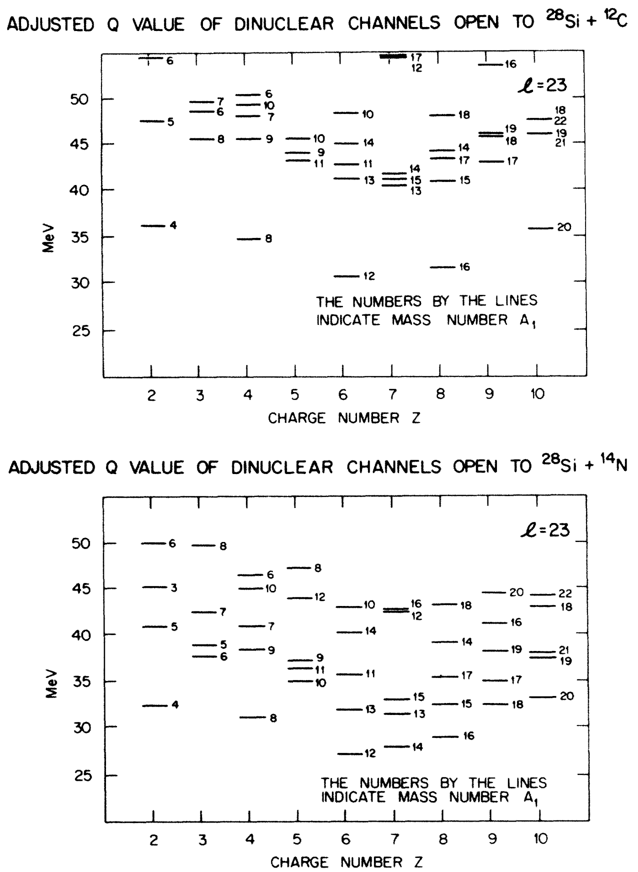

FIG. 1. Potential energies adjusted for Q value of dinuclear particle-transfer channels open to the $^{28}Si+^{12}C$ and $^{28}Si+^{14}N$ interactions. A_1 is the targetlike component of the DNC. The figure illustrates the dramatic difference between the number of channels open to the two interactions at low excitation energies.

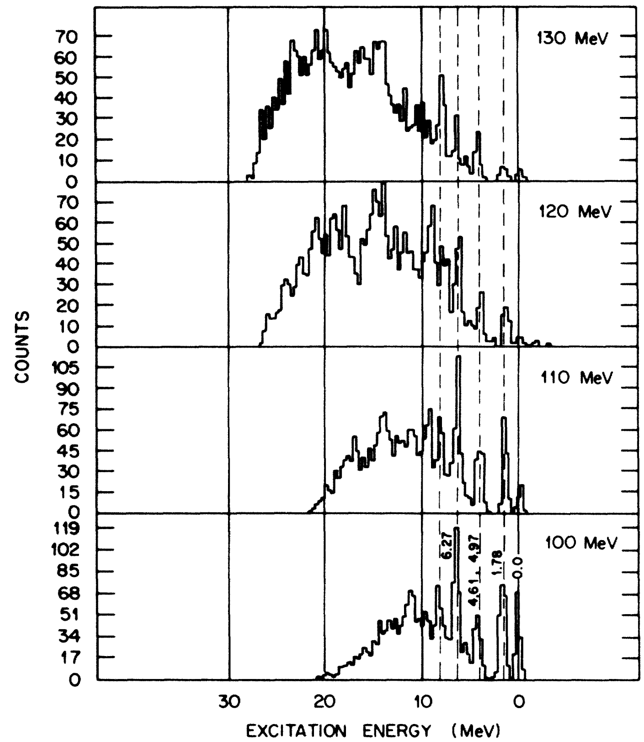

FIG. 2. Yields of ^{14}N nuclei at $\theta_{lab}=5°$ from the $^{28}Si+^{14}N$ interaction plotted as functions of the combined intrinsic excitation energy of the two nuclei. The data have been shown for ^{28}Si laboratory bombarding energies between 100 and 130 MeV.

phase spaces available to each of the exit channels. It is clear that there are several particle-transfer channels accessible to the $^{28}Si+^{14}N$ interaction even at relatively low excitation energies. In stark contrast, the $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems have very few channels accessible at excitation energies (relative Q) ≤ 10 MeV, rendering them inappropriate for studies of mass and charge equilibration. On the basis of energy and phase-space considerations, if the duration of orbiting exceeds the time required for charge and mass equilibration, ^{12}C would be the most common product nucleus in the $^{28}Si+^{14}N$ interaction; otherwise, ^{14}N would be the most common one.

In the measurement reported here, ^{28}Si beams with energies between 100 and 170 MeV, provided by the Oak Ridge National Laboratory Holifield Heavy Ion Research Facility, were used to bombard a ^{14}N supersonic gas-jet target.[9] Targetlike reaction products ($3<Z<10$) were detected at laboratory angles between 3° and 7° corresponding to center-of-mass angles between 165° and 175° in the kinematically reversed reaction (^{14}N beam on a ^{28}Si target). The reaction products were detected at the focal plane of an Enge split-pole spectrograph by a hybrid ionization chamber.[10] By use of the position, energy, and energy-loss signals provided by this detector it was possible to identify the reaction products in terms of both mass and charge.[11]

Figure 2 shows the yields of ^{14}N nuclei from the $^{28}Si+^{14}N$ interaction plotted as functions of the combined intrinsic excitation energy of the two nuclei. The discrete maxima in the spectra can be identified with the combined inelastic excitations in the ^{14}N and ^{28}Si nuclei. Since we are dealing with continuum spectra, it would have been impossible to identify products from target contamination, and thus our use of a ^{14}N supersonic gas-jet target eliminated such complications, as the target is free of impurities and also does not suffer from problems, such as carbon buildup, which are common with solid targets. The background in our experiments has been measured, through studies of elastic scattering, to be negligible. From such spectra (Fig. 2), the extracted kinetic energies and excitation-energy–integrated emission probabilities ($d\sigma/d\theta$) of reaction products are found to be independent of angle as has been observed for the same interaction, over a wider angular range, in a preliminary study.[9] A similar angular dependence has been observed for the orbiting process in several other systems over the whole backward hemisphere.[2] In the forward hemisphere, the orbiting yields are often obscured by other (direct) processes. In all such studies, therefore, the total angle-integrated orbiting cross sections are obtained by the assumption that the angular dependence of the orbiting process, as seen in the backward hemisphere, persists in the forward hemisphere too.

Figure 3 shows the absolute angle-integrated orbiting cross sections for the ^{12}C, ^{14}N, and ^{16}O exit channels plotted as functions of energy. At nearly all incident energies, the ^{12}C and the ^{16}O yields are larger than those of ^{14}N leading to the conclusion that the duration of orbiting in this interaction is sufficiently long to permit charge and mass equilibration. The exit channel with the lowest Q value (see Fig. 1) is found to have the largest cross section. On the basis of energy considerations alone (ground-state Q value or Q_{gg} systematics[12]), for our measurement, the ordering of the yields in decreasing intensity would have been ^{12}C, ^{14}N, and ^{16}O, respectively. The yields from the $^{28}Si+^{14}N$ interaction in fact show this trend at a laboratory energy of 100 MeV. The excess of ^{16}O over ^{14}N, at the higher energies, we believe, is because there is substantially greater phase space available to the $^{26}Al+^{16}O$ channel than to the $^{28}Si+^{14}N$, even though the latter is energetically favored. The number of low-lying energy levels for excitation in the ^{26}Al odd-odd nucleus far exceeds those in ^{28}Si.

It is our opinion that the phase space relevant to a discussion of the orbiting process is that of a dinuclear configuration. Although the saddle (prescission)

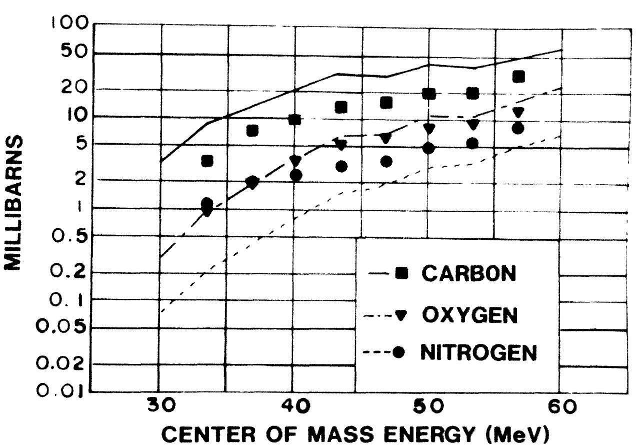

FIG. 3. Orbiting cross sections for the ^{12}C, ^{14}N, and ^{16}O products plotted as functions of center-of-mass energy. The data are shown as points. The curves are the results of a calculation using a dinucleus approach.

shape of a compound nucleus of mass 42 is also dinuclear, compound-nucleus evaporation calculations[13] for the $^{28}Si+^{14}N$ interaction underpredict the orbiting yield by at least a factor of 6, and fail to reproduce the relative $^{14}N/^{16}O$ yield. In a calculation using a dinucleus approach,[14] the relative orbital angular momentum for all exit channels is constrained to a magnitude dictated by the "sticking" conditions in the entrance channel. The presence of this constraint is corroborated by the strong alignment of the products from orbiting interactions, as has been reported recently.[5–8] Also shown in Fig. 3 are some results of such a calculation.[11] The agreement between theory and data is encouraging.

In a comparison of the relative orbiting yields of ^{12}C and ^{16}O nuclei from $^{24}Mg+^{16}O$ and $^{28}Si+^{12}C$ collisions, it had been concluded[4] that the magnitude of this ratio depends on the entrance channel. Such an observation is in contradiction to our claims, based on the present measurement, of a phase-space determination of exit-channel yields. As illustrated in Fig. 1, the $^{28}Si+^{14}N$ system is significantly different from both the $^{28}Si+^{12}C$ and $^{24}Mg+^{16}O$ systems in terms of the number of accessible particle-transfer channels at excitation energies near and below 10 MeV. This is the reported average excitation energy in the $^{24}Mg+^{16}O$ measurement,[4] and since the nucleon-transfer channels are energetically inaccessible, copious particle transfer was not observed. This could account for the strong preference of the $^{24}Mg+^{16}O$ orbiting complex to decay into the entrance channel at these low excitation energies. It is well known from studies of dissipative collisions that vibrational and rotational excitation[15] provide, in addition to particle exchange, a mechanism for energy damping. It is possible that both mechanisms are operative in orbiting reactions. It would be of interest to investigate the $^{24}Mg+^{16}O$ interaction at higher energies to elucidate the relative role of nucleon exchange and inelastic excitation in effecting the dissipation of energy and angular momentum.

In conclusion, we have measured the orbiting yields of reaction products from the $^{28}Si+^{14}N$ interaction. The relative magnitudes of the orbiting yields indicate that the DNC's formed in such interactions live sufficiently long to permit the equilibration of charge and mass. In our measurement both the ^{16}O and the ^{12}C orbiting yields exceed the ^{14}N indicating that there is no preferred direction for mass flow between the interacting nuclei. Since the orbiting yields are typically 10% of the fusion yield, and we believe that the orbiting process reflects how the DNC's formed in such collisions evolve towards fusion, it seems apt to conclude that fusion occurs not through a process of continual particle exchange whereby one nucleus is gradually consumed by the other, but by a change of shape of a dinuclear system that retains its mass asymmetry. These ideas bear further investigation.

Discussions with S. Ayik, F. E. Bertrand, Jr., and D. J. Horen are gratefully acknowledged. This work was supported in part by Contract No. DE-AC02-76ER0374 with the U.S. Department of Energy. Oak Ridge National Laboratory is operated by Martin Marietta Energy Systems, Inc., under Contract DE-AC0584OR21400 with the U.S. Department of Energy.

[1]R. Eggers *et al.*, Phys. Rev. Lett. **37**, 324 (1976).

[2]D. Shapira *et al.*, Phys. Rev. Lett. **53**, 1634 (1984).

[3]I. Iori *et al.*, Phys. Lett. **132B**, 304 (1983).

[4]A. Ray *et al.*, Phys. Rev. C **31**, 1573 (1985).

[5]W. Dünnweber *et al.*, in Proceedings of the Second International Conference on Nucleus-Nucleus Collisions, Visby, Sweden, 10–14 June 1985 (unpublished), Vol. 1, p. 119.

[6]A. Glaesner *et al.*, Phys. Lett. **169B**, 153 (1986).

[7]A. Ray, Ph.D. thesis, University of Washington, 1986 (unpublished).

[8]A. Ray *et al.*, to be published.

[9]D. Shapira *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. B **10&11**, 436 (1985).

[10]D. Shapira *et al.*, Nucl. Instrum Methods **169**, 77 (1980).

[11]B. Shivakumar, Ph.D. thesis, Yale University, 1986 (unpublished), and to be published.

[12]V. V. Volkov, Fiz. Elem. Chastits At. Yadra **6**, 1040 (1975) [Sov. J. Part. Nucl. **6**, No. 4, 420 (1976)].

[13]D. Shapira *et al.*, to be published.

[14]B. Shivakumar *et al.*, to be published.

[15]R. A. Broglia *et al.*, Phys. Lett. **61B**, 113 (1976).